

Sustainable energy systems for a remote island community



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HIGHLIGHTS

- We design a tri-generation system to support cooling, heating and power needs of an island.
- Three schemes of renewable energy penetrations – peak shaving, 20% and 40% penetration.
- Reductions of approximately 20% in primary energy savings are realizable for all three cases.
- Renewable energy penetration level of 40% yielded the largest reduction of CO₂ emission.

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ABSTRACT

This paper evaluates the potential of integrating renewable energy technological resources for tri-generation applications in an island. The integrated tri-generation system has to be self-sustaining in delivering cooling, heating and power. Several CCHP (combined cooling heating and power) systems at different penetration levels were proposed. The CCHP systems comprising key prime movers include microturbines, photovoltaic, solar Stirling dish, fuel cell system, biomass power generator and an absorption cooling technology. The systems are judiciously designed to provide the island's tri-generation needs. Three different operational schemes of varying renewable energy penetration were considered – peak shaving, 20% and 40% renewable energy penetration. Key results have suggested that reductions of approximately 20% in primary energy savings are realizable for all three cases. Additionally, a renewable energy penetration level of 40% yielded the largest reduction in terms of carbon dioxide emission. In terms of cost benefits for the proposed system combinations, peak shaving and 20% renewable energy penetration can realize savings of up to USD \$150,000 per annum.

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1. Introduction

The Energy Market Authority (EMA) of Singapore has embarked on a pioneering project in Southeast Asia to develop an intelligent micro-grid infrastructure with clean and renewable technologies in Pulau Ubin, an island northeast of Singapore. This project could potentially transform part of the island into a model 'green' island powered entirely by clean and renewable energy [1] and also boost Singapore's ambition to be a global test-bedding site for new energy technologies. The modest power demand of Pulau Ubin means that it would be uneconomical to lay power transmission cables to the island. As such, the island is currently supported by diesel generators and, therefore, it exhibits a great potential for test bedding a micro-grid system with distributed generation using clean and renewable energy resources.

Despite extensive research works being done on renewable energies, the needs to provide islands with energy alternatives for future development are only modestly discussed in various literatures [2–4]. Chen et al. [5] have highlighted that most remote island energy system studies focused on standalone hydrogen systems powered by renewable energy technologies such as wind and solar power. The difficulties in integrating various renewable energy technologies into energy systems were also highlighted [5]. There are available works that studied the deployment of renewable energy systems for an island. However, these works focus on specific renewable technologies such as wind-turbine or PV. For example, Bueno and Carta focused on employing wind powered pumped hydro storage systems as a means of increasing the penetration of renewable energy in the Canary Islands [6]. Duić and da Graça Carvalho and Deshmukh and Deshmukh have studied hybrid systems that combined PV–wind to generate power to supplement the energy needs of islands [7,8]. Others have relied on conventional renewable energy technologies such as PV, diesel generators, wind turbine generators, PV system and batteries to generate power for isolated islands [9–11]. Compared with these

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A_{proj}	projected area of SSD mirror, m ²
C_{ann}	annualized cost, US\$
$Capacity_{rated}$	rated capacity of equipment, kJ/h
C_c	capital cost, US\$
CCHP	combined cooling, heating and power
$c_{coolant}$	heat capacity of SSD coolant fluid, kJ/kg K
CESR	carbon dioxide emission ratio
CE	carbon dioxide emission
C_{fuel}	fuel cost, US\$
c_h	heat capacity of SSD working fluid, kJ/kg K
$C_{O\&M}$	operations and maintenance costs, US\$
COP	coefficient of performance
c_p	Heat capacity, kJ/kg K
d	discount rate, %
e	fuel escalation rate, %
f	Stirling engine frequency
F	Faraday's constant
$f_{DesignEnergyInput}$	fraction of absorption chiller design capacity
G_{DNI}	direct normal insolation, W/m ²
G_T	total radiation incident on PV array (W), W/m ²
I	current, A
I_D	diode current, A
I_{Ely}	electrolyzer current, A
I_L	PV module photocurrent, A
I_o	diode reverse saturation current, A
LF	Levelizing factor
LHV	lower heating (calorific) value, kJ/kg
$\dot{m}_B M$	mass flow rate, kg/h
$(\dot{m}c)_{min}$	minimum capacitance rate of SSD coolant fluid
MT	microturbine
n	no. of moles
$\dot{n}_{H_2}$	hydrogen production rate
N	life cycle of plant, years
N_{cells}	number of electrolyzer cells connected in series
N_{H_2}	hydrogen fuel supply to fuel cell, kmol/s
p	pressure, Pa
P_{demand}	total electricity demand of island, kW
PESR	primary energy savings ratio
P_{Gross}	SSD gross power production, kW
$P_{in,SE}$	solar Stirling dish thermal input power, kW
$P_{in,rec}$	power intercepted by SSD receiver, kW
p_{mean}	mean Stirling engine pressure, Pa
P_{MT}	power supplied by microturbine, kW
P_{PV}	power supplied by photovoltaic, kW
P_{SOFC}	power supplied by fuel cell, kW
P_{SSD}	power supplied by solar Stirling dish, kW
P_{tur}	turbine power, kW
$\dot{q}_{cond\ losses}$	SSD receiver thermal conduction losses, kW
$\dot{q}_{cond,tot\ losses}$	total SSD receiver thermal convection losses, kW
q_{HX}	heat exchanged in fuel cell heat exchanger, kJ
$\dot{q}_{rad,emitlosses}$	SSD radiation emission losses, kW

$\dot{Q}_{rad,reflect}$	SSD reflected radiation, kW
$\dot{Q}_{aux,chiller}$	energy draw of parasitics by absorption chiller, kW
Q_{SSD}	heat produced by SSD, kW
R	universal gas constant
R_s	PV module series resistance, Ω
R_{sh}	PV module shunt resistance, Ω
$T_{coolant}$	temperature of SSD coolant fluid, K
T_{exh}	temperature of exhaust gases in fuel cell heat exchanger, K
T_h	temperature of SSD working fluid, K
T_{PV}	PV module temperature, K
T_{water}	temperature of water entering/exiting fuel cell heat exchanger, K
$(UA)_{eff}$	effective heat transfer coefficient, W/m ² K
v	specific volume, m ³ /kg
V	voltage, V
Vol	volume of H ₂ gas tank, m ³
V_{sw}	Stirling engine swept volume, m ³

ε_{FC}	electrical efficiency of fuel cell power module
Δh	change in enthalpy, kJ/kg
η	Efficiency
ρ_{ref}	SSD mirror reflectivity
$\varphi_{int,fac}$	fraction of energy reflected from parabolic concentrator of SSD
φ_{shade}	shading factor of SSD
φ_{wind}	wind speed at which SSD is sent into stow position, m/s

<i>aux</i>	auxiliary
<i>Abs</i>	absorption chiller
<i>boiler</i>	boiler
<i>BM</i>	biomass
<i>chw</i>	chilled water
<i>comp</i>	compressor
<i>cw</i>	cold water
<i>el</i>	electricity
<i>hw</i>	hot water
H_2	hydrogen gas
<i>in</i>	inlet conditions
<i>is</i>	isentropic
<i>mech</i>	mechanical
<i>mp</i>	at maximum power point
<i>ref</i>	at reference conditions
<i>res</i>	renewable energy system
<i>th</i>	thermal
<i>tur</i>	turbine
<i>out</i>	outlet conditions

Integrating renewable energy technologies enables carbon emission due to power generation to be significantly trimmed.

The over-reliance of conventional fuel to generate power generation motivates the evolution of new energy generation systems in order to meet multiple needs as well as to realize greater energy efficiency; translating to greater fuel cost savings. The development of tri-generation system serves to mitigate the high cost of renewable energy technologies in order to engineer a cost effective energy generation system that produces heating, cooling and power independently to support an island's key demands, namely, electricity power, cooling and heating. Tri-generation system, also known as combined cooling, heating and power (CCHP) system

offers more efficient utilization of energy through recovery of waste heat from power generation for cooling and heating. There are several key merits in proposing and adopting the CCHP system with operating schemes compared the base system when electricity generated by a single prime mover, in the case microturbine, is utilized to support power, cooling and heating needs. Firstly, CCHP system depends on the synergetic roles of individual prime movers to provide tri-generation whereby waste-heat can be converted to provide cooling through heat-driven chillers and to meet heating needs [12]. Primary energy savings is therefore to be expected. Secondly, lower primary energy utilization is expected to translate to reduced carbon emission compared to systems without CCHP capabilities [13]. Thirdly, high overall efficiency can be realized [14].

Lin and co-workers [15] have demonstrated that an increase in the total thermal efficiency from 22.1% to 67.3% is possible when tri-generation system is employed instead of single generation units. Studies have also shown that some of the largest carbon savings can be made more cost effectively through the use of power plants that integrates renewable sources in CCHP systems [16]. Day and his team have demonstrated that CCHP systems can potentially provide a further 5.8% in CO₂ reduction for power plants [17]. Hence, through the integration of renewable sources, a hybridization of tri-generation system with renewable energy can result in (a) a more efficient use of fossil fuel through tri-generation; (b) a diversification of energy resources; and (c) a lower carbon dioxide emission through the proper integration of renewable energy technology.

The main motivation of this study is to judiciously design an integrated energy system whereby renewable energy technologies such as solar power and biomass are developed to support tri-generation or CCHP operations. The integrated tri-generation system aspires to (a) meet the heating, cooling and power demands of the island, (b) reduce the resulting carbon emission due to the tri-generation operation; and (c) minimize the primary energy consumption by reducing the use of fuel. Based on these targets, we have carved out the specific objectives of this study. They are (a) to study the potential of integration various renewable energy options on of Pulau Ubin; (b) to investigate the energy, cooling and heating needs of the island; (c) to develop a standalone integrated energy system framework to support tri-generation; and (d) to evaluate the system performance in terms of economic costs, carbon emission and primary energy savings. Certainly, the proposed renewable system is to augment the island's energy needs for new developments (e.g. new infrastructure – hotels, shopping malls, etc.) and reduce total reliance on grid power. The proposed CCHP configuration is designed based on Singapore's unique geographical position and the island needs. Already, the Singapore government has considered implementing the proposed configuration on a designated island [1].

It should be highlighted that it is not the intent of this study to conduct a detailed optimization scheme for the proposed tri-generation system due to its level of complexity. Rather the study ought to be treated as a first-cut in designing a feasible integrated renewable system to support key needs of an island. Several potential design scenarios are then evaluated and compared based on their economic costs, carbon emission and energy saving merits. Though much has been written about the technological side of renewable systems, the challenges these developments pose in terms of overall energy efficiency and overall carbon emission generation are less frequently addressed. One key feature of the present integrated system includes its ability to support tri-generation (electrical/cooling/heating needs) while aspiring to improve overall system energy efficiency and reducing the overall carbon emission of the system. Such an encompassing study has yet to be carried out by others to the best of our knowledge.

2. Island description and energy demands

Pulau Ubin, with a population of about 200, is an island north-east of Singapore with a land size of 1020 hectares. Presently, due to its modest energy needs, inhabitants of Pulau Ubin rely on diesel generators for their energy needs as it is not connected by grid to mainland Singapore. An idyllic getaway for both Singaporeans and tourists, Pulau Ubin has the potential to be developed into a popular tourist destination with amenities such as hotels, resorts and restaurants. Our proposed integrated energy system is designed based on the power, heating and cooling demands of a 5 storey hotel, 3 resorts, 8 restaurants and 30 residential homes as shown in Table 1.

To estimate the energy needs, the enhanced DOE-2.2-derived user interface eQuest was adopted for simulating the power, cooling and heating demands of the island. eQuest is a building energy analysis tool which allows users to simulate the hourly energy use and energy cost of a building given user inputs of hourly weather data, building model descriptions and its Heating, Ventilating and Air conditioning (HVAC) equipment [18].

Results from the energy simulation for the total monthly cooling, heating and power demand of the island for the year are presented in Fig. 1. Fig. 2 shows the power, heating and cooling

Table 1
Parameters for simulated facilities.

Building Type	No. of units	Floor Area per facility (square meters)	Description
5 Storey hotel	1	10,219	1 Basement level
Resort	3	6039	
Restaurants	8	465	Assumed operation hours from 11 am to 11 pm
Residential homes	30	140	Single family unit

Table 2
Key operating parameters for reference case.

Component	Parameter	Value
Microturbine	Capacity	780 kW
	Overall electrical efficiency	35%
	Capital cost	\$780,000
	Operation and maintenance	\$0.01/kWh
	Fuel costs	\$1.1/kg
Vapor compression chiller	Capacity	1000 kW
	COP	4.3
	Capital cost	\$148,000
Boiler	Capacity	230 kW
	Efficiency	80%
	Capital cost	\$10,580

Table 3
Installed capacity of various power generation technologies for various cases.

	Installed capacity (kW)					
	MT	Absorption chiller	Biomass	PV	SSD	SOFC
Case 1a	520	512	150	200	125	200
Case 1b	520	512	150	200	250	200
Case 1c	520	512	200	200	125	200
Case 2a	430	418	200	300	375	300
Case 2b	430	418	200	300	500	300
Case 2c	430	418	200	400	375	300
Case 3a	365	330	300	500	1000	350
Case 3b	365	330	300	500	750	350
Case 3c	365	330	300	750	750	350

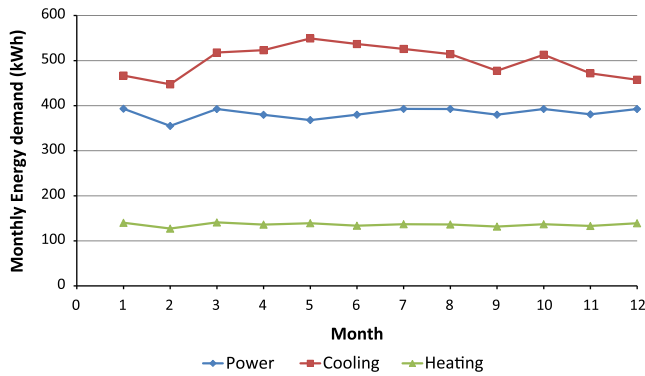


Fig. 1. Energy simulation for the total monthly cooling, heating and power demand of the island.

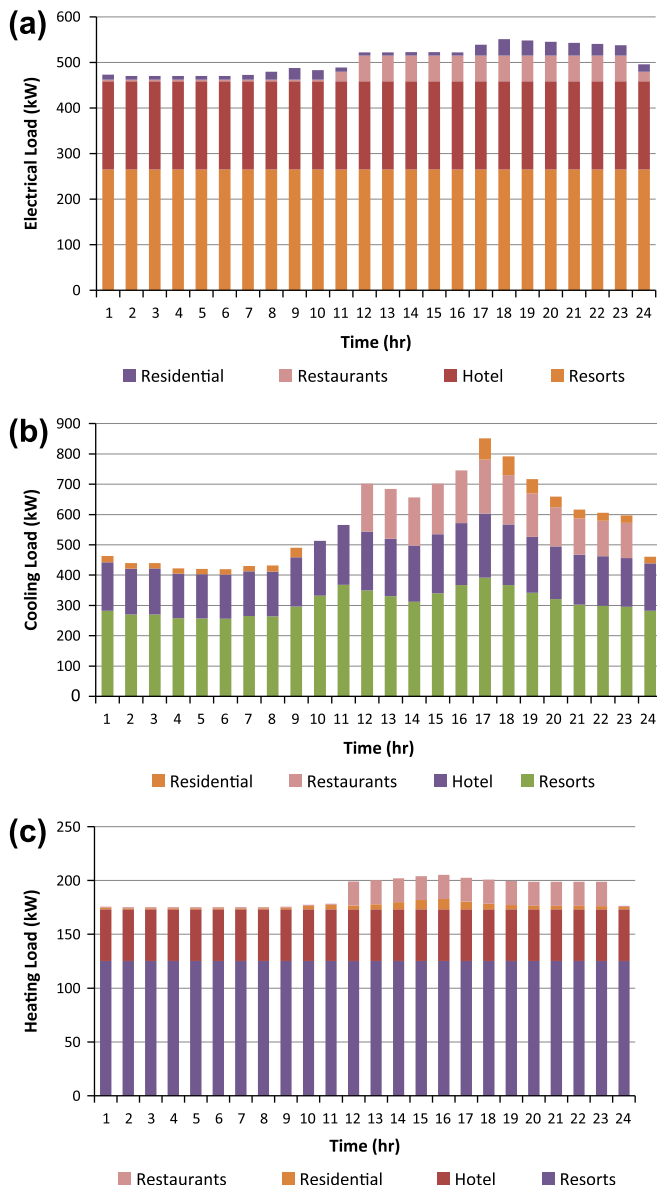


Fig. 2. Hourly load demand of island: (a) electrical load, (b) cooling load, (c) heating load.

demands of the island for a typical day in January on an hourly basis. The daily power, cooling and heating load profiles are assumed to remain constant throughout the month. Cooling demand refers

to the thermal energy required to be removed from a facility by the HVAC equipment. Power demand refers to the electricity needed in order to power appliances such as equipment and lighting. Due to the tropical climate of Singapore, heating demand is limited to hot water used for activities such as cooking, bathing and washing.

3. Mathematical model development

3.1. System description

Based on the available resources, existing infrastructure and existing renewable energy technologies, an integrated system is conceptualized. A schematic illustrating the integrated system is depicted in Fig. 3. The central grid control provides an electrical balance for the system. In the event of a power deficit, the system either switches on the biomass plant to generate the required electricity demand or employs the fuel cell to make up for the deficit depending on the hydrogen tank levels.

The integrated tri-generation system comprises mainly of the following key components:

- **Microturbine:** Represents the core of the integrated tri-generation system which is driven by natural gas. It produces electrical energy and cogenerated heat through waste heat recovery system to thermally drive absorption chillers.
- **Single effect absorption chiller:** It utilizes excess heat from the microturbine and produce cooling energy. These chillers are heat-driven. Compared to mechanical chillers, they have relatively low coefficient of performance (COP). As a result, they are considered as ‘poor’ energy converters. Hence, typically in tri-generation system, the absorption chiller operates such that no extra heat is generated in order to be converted to cooling. The single effect absorption chiller is estimated to have a COP of 0.76;
- **Biomass cogeneration plant:** Fuelled by wood chips, the biomass plant operates to supplement any power deficit. The biomass plant produces both electricity and cogenerated heat to provide for both the power and heating needs of the island.
- **Photovoltaic (PV):** Produces only electricity from solar radiation. Each of the PV module is rated at 230 W; the total power output of the PV unit can be increased by either connecting the modules in series or parallel;
- **Solar Stirling Dish (SSD):** Comprises 25 kW individual units. It converts solar power into mechanical energy to produce both electricity and heat through cogeneration;
- **Fuel cell system:** Comprises solid oxide fuel cell (SOFC), electrolyzer and hydrogen storage. The SOFC operates *if and only if* there is a power deficit and sufficient available hydrogen. Power surpluses that are generated from the integrated system will be stored through the production of hydrogen from the electrolyzer;
- **Mechanical chiller:** Utilizes electric energy in order to produce cooling. The chiller typically has a higher COP compared to absorption chiller and is conventionally preferred over absorption chiller in the absence of waste heat. A COP of 4.3 is assumed for the mechanical chillers; and
- **Auxiliary boiler:** Supplements the thermal demands of the absorption chiller and the heating load of the island. An efficiency of 80% is assumed.

3.2. System modeling

The tri-generation system, shown in Fig. 3, is modeled using TRNSYS 17 simulation tool. TRNSYS 17, abbreviation for ‘Transient

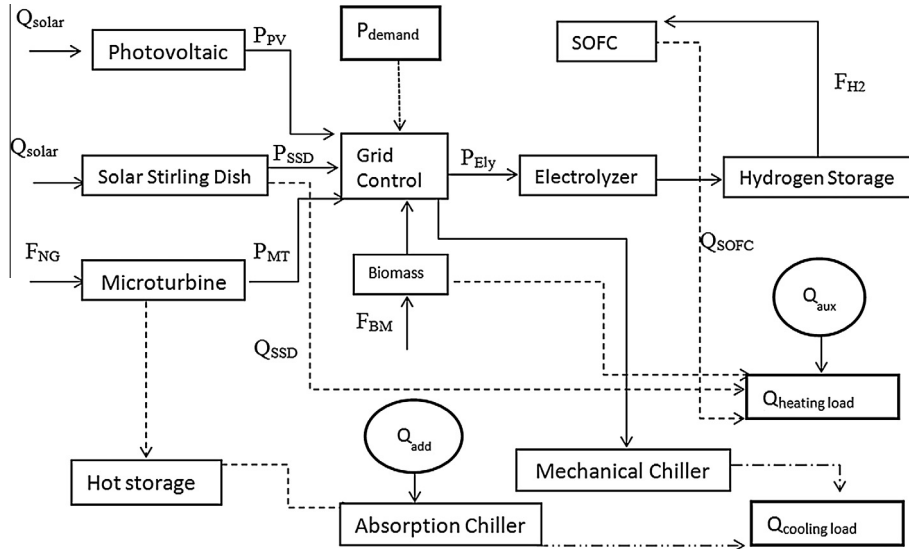


Fig. 3. Proposed renewable energy technologies integration to provide for tri-generation needs.

System Simulation Program' adopts an open modular structure to simulate the electricity and heat sectors of an energy-system by breaking it down into individual components [19]. It is primarily used for analyzing single-project, local community or island energy-system [20]. TRNSYS has been used extensively in the study of energy systems especially due to its ability to simulate heat and electricity. Amongst the various studies include the modeling of a hybrid photovoltaic thermal system in Cyprus [21]. In addition, Quesada et al. [22] have also experimentally validated the use of TRNSYS model on a 7.2 kWp grid-connected photovoltaic system.

TRNSYS 17 is a quasi-steady/transient simulation program model. It contains sub-routines that model a variety of energy system having key equations presented in terms of their ordinary differential or algebraic equations. TRNSYS 17 is capable of interconnecting different system components in a tailored design. In the TRNSYS 17 simulating platform, the iteration solution proceeds in several steps. Firstly, each component subroutine is designed to compute the output from the sub-models based on the supplied information. Secondly, the outputs of the component are connected to the inputs of other sub-models. Thirdly, the iteration of the tri-generation system continues until all the sub-routines have converged. Fig. 4 shows a detailed schematic of the integrated renewable energy system in TRNSYS environment for which components are adopted from the component library package. Some of the components obtained from the TRNSYS include (i) electrical components; (ii) HVAC (Heating Ventilation Air-Conditioning) components; (iii) solar components; (iv) storage system components; (v) cogeneration (CHP) components and (vi) high temperature solar components. Other components for prime-movers such as microturbine, biomass and SOFC were developed in-house using key governing equations.

3.2.1. Microturbine

The microturbine model comprises a gas compressor, gas turbine, combustion chamber, a recuperator and an electric generator. Both gas compressor and gas turbine models calculate the outlet conditions from its inlet state by using their respective isentropic efficiencies. Gas compressor depends on the input gas or air to compress it to the desired outlet gas or air condition whereas the gas turbine produces work from the input gas.

For compressor, the governing equations are as follows:

$$\Delta h_{comp} = \frac{h_{out,is} - h_{in}}{\eta_{is,comp}} \quad (1)$$

$$P_{comp} = \frac{m_{out} \times \Delta h_{comp}}{\eta_{mech,comp}} \quad (2)$$

For the turbine, the governing equations are as follows

$$\Delta h_{tur} = \frac{h_{tur,in} - h_{out,is}}{\eta_{is,tur}} \quad (3)$$

$$P_{tur} = m_{in} \times \Delta h_{tur} \times \eta_{mech,tur} \quad (4)$$

The combustion chamber is assumed to undergo an adiabatic combustion process given fuel properties input defined by the lower heating value. The fuel used for this study is natural gas. The recuperator model employs the NTU- ϵ method to predict the combustion chamber gas inlet conditions given the compressor and turbine gas outlet conditions by employing the different recuperator effectiveness correlation. The net power generation P_{MT} from the microturbine is computed from the difference between the gas turbine power output P_{tur} and the compressor power input P_{comp} and accounting for the electric generator efficiency.

3.2.2. Absorption chiller

The absorption chiller is a single-effect hot water fired chiller. The catalog data used is based on a Broad Chiller Single-stage hot water chiller with a rated COP of 0.76 [23]. In this model, the heat required to thermally drive the absorption chiller is provided by a hot water stream. The model first determines the fraction of the design load $f_{DesignEnergyInput}$ which it operates on by calculating the amount of energy that must be removed from the chilled water stream in order to bring it to the set point temperature.

$$\dot{Q}_{chw} = m_{chw} \times C_{pchw} \times (T_{chw,in} - T_{chw,set}) \quad (5)$$

The fraction of the chiller's design capacity $f_{DesignEnergyInput}$ at which it is operating at is first determined. The total energy delivered to the chiller by the hot water Q_{hw} is then given by

$$\dot{Q}_{hw} = \frac{Capacity_{rated}}{COP_{rated}} \times f_{DesignEnergyInput} \quad (6)$$

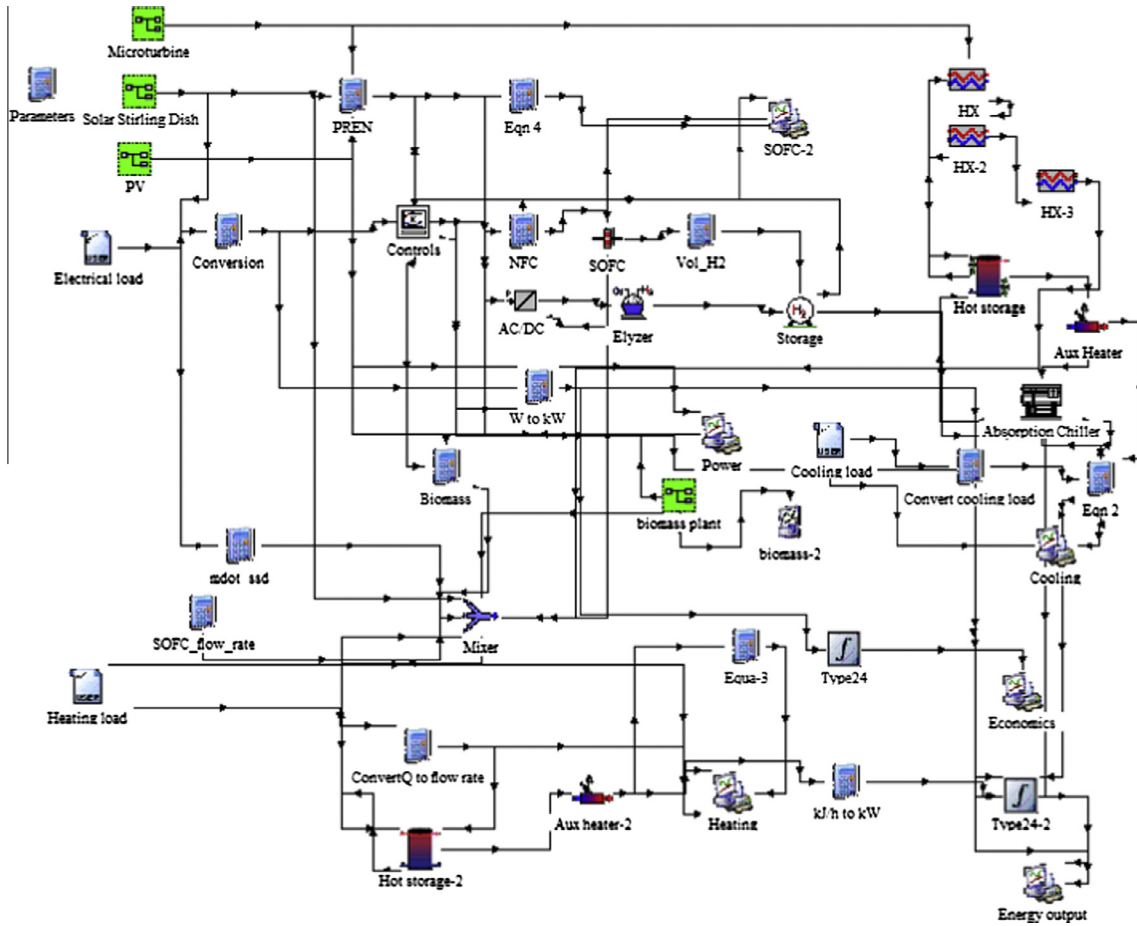


Fig. 4. Schematic diagram of integrated energy system in TRNSYS environment.

The total energy ejection to the cooling water stream is calculated by accounting for the parasitic losses using an energy balance

$$\dot{Q}_{cw} = \dot{Q}_{chw} + \dot{Q}_{hw} + \dot{Q}_{aux,chiller} \quad (7)$$

3.2.3. Photovoltaic

The PV is modeled using an equivalent electrical circuit comprising a real diode connected in parallel with an ideal current source, a series resistance and a shunt resistance. The insolation and temperature dependence of the PV module are given by

$$I_L = I_{L,ref} \times \frac{G_T}{G_{T,ref}} \quad (8)$$

$$\frac{I_o}{I_{o,ref}} = \left(\frac{T_{PV}}{T_{PV,ref}} \right)^3 \quad (9)$$

In many applications, PV is usually connected to a maximum power point tracking device which ensures that the maximum power output is obtained. Once I_o and I_L are found from the above equations, an iterative search routine, performed in TRNSYS, finds the current I_{mp} and voltage V_{mp} at the maximum power along the IV curve. The power output of the PV at MPPT is given by

$$P_{PV} = I_{mp} \times V_{mp} \quad (10)$$

3.2.4. Solar Stirling dish

For the SSD model, the Fraser model is adopted [15]. The model has been developed with the support from the National Renewable

Energy Laboratory using data from the WGA Stirling dish system [24]. The Fraser Model comprises three main components of the SSD system: parabolic concentrator, receiver and a Stirling engine.

For the parabolic concentrator model, the power intercepted by the receiver $P_{in,rec}$ is given by

$$P_{in,rec} = G_{DNI} \times A_{proj} \times \varphi_{wind} \times \varphi_{int,fac} \times \varphi_{ref} \times \varphi_{shade} \quad (11)$$

For the receiver model, the thermal input power $P_{in,SE}$ to the Stirling engine is computed by

$$P_{in,SE} = P_{in,rec} - \dot{q}_{rad,reflect} - (\dot{q}_{cond} + \dot{q}_{conv,tot} + \dot{q}_{rad,emit})_{losses} \quad (12)$$

For the Stirling engine model, the gross power P_{Gross} generated by the Stirling engine is given by Eq. (13). A correction term $n_{correct}$ developed by MaMahan et al. [25] is used to improve the accuracy of the gross power prediction.

$$P_{Gross} = Beale_{curve} \times [P_{mean} \times V_{sw} \times f \times n_{correct}] \quad (13)$$

The net system power P_{SSD} produced by the SSD is obtained by subtracting the parasitic powers due to the tracking and control from the gross power. The NTU- ϵ model is adopted for the shell-and-tube cooler employed in the SSD's cooling system. To exploit the Stirling dish system's cogeneration capability, the Fraser Model has been appropriately modified to enable waste heat recovery for cogeneration. The waste heat recovered Q_{SSD} is given by

$$Q_{SSD} = \dot{m}_{coolant} \times c_{coolant} \times (T_{coolant,out} - T_{c,in}) = \epsilon \times [(\dot{m}c)_{min} \times (T_{hin} - T_{coolant,in})] \quad (14)$$

3.2.5. Fuel cell system

The fuel cell system model comprises of an SOFC, electrolyzer and compressed gas storage for H₂. The fuel cell model adopted is an SOFC cogeneration model developed by IEA Annex 42 [26]. The model comprises primarily: a Fuel Cell Power module (FCPM) and a heat recovery system for cogeneration.

For the electrical model, the net electric power P_{FC} produced by the FCMP is obtained by

$$P_{SOFC} = \varepsilon_{FC} \times \dot{N}_{H_2} \times LHV_{H_2} \quad (15)$$

For the heat recovery system, an exhaust Gas-to-Water heat exchanger is used. The exhaust Gas-to-Water heat exchanger employs a log mean temperature difference (LMTD) method to determine the heat recovery,

$$q_{HX} = (UA)_{eff} \times \frac{(T_{exh,out} - T_{water,out}) - (T_{exh,in} - T_{water,in})}{\ln \left(\frac{T_{exh,out} - T_{water,out}}{T_{exh,in} - T_{water,in}} \right)} \quad (16)$$

For the electrolyzer, the total hydrogen production rate is determined from several cells connected in series and can be expressed by

$$\dot{n}_{H_2} = \eta_f \times N_{cells} \times \frac{I_{Ely}}{n_e \times F} \quad (17)$$

For the compressed gas storage, the governing equation is based on the Van der Waal's equation of state given by

$$p = \frac{n_{H_2} \times R \times T_{gas}}{Vol - (n_{H_2} \times b)} - \frac{a \times n_{H_2}^2}{Vol^2} \quad (18)$$

where a and b are constants accounting for intermolecular attraction forces and volume occupied by the gas molecules respectively.

3.2.6. Biomass plant

The biomass plant model adopted is the organic Rankine cycle which comprises of mainly four components: boiler, condensate pump, condenser and a turbine to generate electricity. Waste heat is recovered through heat exchange within the condenser for cogeneration.

For the boiler, the change in enthalpy of steam is given by

$$\dot{m}_{steam} \times \Delta h = Capacity_{rated,boiler} \times \eta_{combustion} \times \eta_{boiler} \quad (19)$$

in which the capacity of the boiler $Capacity_{rated,boiler}$ depends on the biomass fuel input governed by the equation shown below.

$$Capacity_{rated,boiler} = \dot{m}_{BM} \times LHV_{BM} \quad (20)$$

The condenser relies on the pinch point temperature difference approach to solve for the heat transfer between the condensing steam and the cooling fluid. In this model, the saturation pressure of the steam is calculated such that the pinch point temperature is just reached at the critical point in the condenser.

3.2.7. Energetic efficiency

To assess the comparative advantage of CCHP compared to conventional separate production methods and to evaluate CCHP's contribution to the reduction to global energy flows, we adopted the Primary Energy Savings Ratio (PESR) parameter. Briefly, the PESR evaluates the technical performance of a tri-generation plant by comparing its performance with separate energy, cooling and heat production means on annual basis [27].

$$PESR = \frac{\sum_t F_t^{SP} - \sum_t F_t^{CHP}}{\sum_t F_t^{SP}} = 1 - \frac{\sum_t F_t^{CHP}}{\sum_t F_t^{SP} + \sum_t \frac{m_t^{CHP}}{\eta_{el}^{SP}} + \sum_t \frac{C_{o,t}^{CHP}}{\eta_{el}^{SP} \times COP^{chiller}}} \quad (21)$$

3.2.8. Environmental impact

For this part of the study, the environmental impact of the proposed tri-generation system is evaluated using the life cycle analysis (LCA) approach. The key advantage of using the LCA approach is that LCA is a 'cradle-to-grave' assessment which accounts for significant environmental impacts from both direct and indirect emissions. While direct emission accounts for carbon emission during the actual energy production, indirect emissions refer to emissions resulting from phases such as plant construction phase, installation and decommissioning of the plant. Henceforth, LCA provides a more pragmatic accounting of the carbon dioxide resulting from power generation from various renewable technologies. LCA allows decision makers to make better decisions pertaining to environmental protection [28]. LCA is measured in terms of carbon emission equivalent (g-CO₂/kW h) of greenhouse gas emission. The carbon dioxide emission as a result of direct combustion of natural gas is taken at 370 g-CO₂/kW h [29]. Table 4 summarizes the carbon emission from power generation resulting from the various technologies.

To account for the relative saving in carbon emission for each case, the parameter carbon dioxide emission saving ratio (CESR) is introduced. CESR is defined as the ratio of the difference between various renewable energy systems and reference case to that of the reference case. To recap the reference case refers to a system whereby power is generated solely by a microturbine without CCHP capabilities. In short, CESR is given as

$$CESR = \frac{CE_{res} - CE_{ref}}{CE_{ref}} \quad (22)$$

3.2.9. Annualized life cycle costing

Life cycle cost includes the sum of the total costs of the system over the life of the system or selected period of analysis, n , in today's dollars, taking into time value of money and fuel escalation rates. Annualized life cycle savings, $C_{ann.savings}$, refer to the difference between the life cycle costs from operating the hybrid tri-generation plant as compared to conventional separate generation methods [30,31]. The annualized life cycle cost for the plant comprises three components: (1) total capital cost C_c , (2) operation and maintenance cost $C_{O\&M}$ and (3) cost of fuel C_{fuel} expressed by

$$C_{ann} = (C_c \times C_{RF}) + C_{O\&M} + (C_{fuel} \times LF) \quad (23)$$

where C_{RF} is known as the capital recovery factor accounting for discount rate d given by

$$C_{RF} = \frac{d \times (1 + d)^N}{(1 + d)^N - 1} \quad (24)$$

LF is the leveling factor accounting for fuel escalation rates given by

$$LF = \left[\frac{(1 + d')^N - 1}{d' \times (1 + d')^N} \right] \times \left[\frac{d \times (1 + d)^N}{(1 + d)^N} \right] \quad (25)$$

where d is discount rate and d' is the effective discount rate given by $d' = \frac{d-e}{1+e}$ accounting for the fuel escalation rate, e . The various

Table 4
LCA for renewable power generation technologies.

Technology	CO ₂ emission (g-CO ₂ /kWh)	Reference
PV	165	[32]
SSD	13	[33]
SOFC	218.5	[34]
Biomass	62.5	[35]

Table 5

Economic data of various power generation and auxiliaries technologies.

Technology (main prime movers in bold) and auxiliaries	Capital cost	Operation and maintenance	Cost of fuel	Life cycle n , years	Reference
Microturbine	\$1000/kW	\$0.01/kWh	\$1.10/kg	10	[36,37]
PV	\$4.185/Wp	0.15% of capital cost	-	30	[38,39]
SSD (25 kW unit)	\$59,966.50/unit	\$1250/year	-	30	[40,41]
SOFC (5 kW unit)	\$4000/unit	\$400/year	-	6	[42,43]
Biomass	\$3600/kW	10% of capital cost	\$ 130/tonne	15	[44–46]
Electrolyzer	\$400,000/unit	-	-	10	[47,48]
Hydrogen storage	\$46,072/unit	-	-	20	[47,49]
Absorption	\$103,500 ^a	-	-	20	[50]
Chiller	\$146,300 ^b , \$147,630 ^c	-	-	-	-
Boiler	\$46/kW	-	-	30	[51,52]

^a Interpolated rated capacity of 330 kW.^b Rated capacity of 418 kW.^c Rated capacity of 512 kW.

economic costs for the individual power generation technologies and auxiliary components are summarized in Tables 5.

4. Investigating case studies

For this study, three schemes of operations are proposed at varying degrees of renewable energy penetration – *peak shaving strategy*, *20% and 40% renewable penetration*. According to several works on renewable energy systems, energy penetration is best promoted through an unfolding stage-by-stage approach [53,54]. Based on the exorbitant cost of implementing renewable energy and the desired emissions reduction, literatures have suggested its penetration to be below 50% [55–57]. Hence, three scenarios with a maximum of 40% were proposed in this study.

For each case, variations of the sizes of the renewable energy technologies are selected for study on the effect of the impact that each technology has on the results. The cases are as summarized in Table 3. The main objective of designing these three schemes is to investigate the impacts of gradually increasing the renewable energy penetration. In order to compare the benefits of the various operation schemes, the designed systems are compared to that of a reference case whereby power, heating and cooling are generated by separate production means.

4.1. Reference case

For the reference system, power is generated solely by a microturbine without CCHP capabilities. That is, heating, cooling and power are generated by separate means. The operating parameters

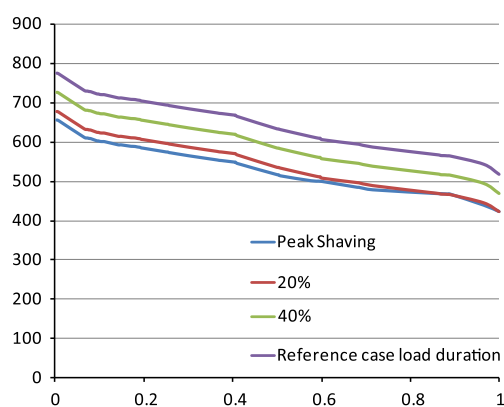


Fig. 5. Resulting electricity load demand curve for reference case, peak shaving strategy, 20% and 40% renewable penetration.

for various components in the reference system are assumed and tabulated in Table 2. The mechanical chiller draws power from the integrated energy system to sustain its operations. Therefore, it adds to the total power demand that the microturbine has to support. The resulting electricity load demand curve is shown in Fig. 5. Capacity factor utilization is a measure of the output of a plant for a specific duration compared to the maximum output it could produce for the same period and may be quantified by the load duration curves [58]. Due to the compactness and some rounding-up of the plotted simulation data, the simulated lines portrayed in Fig. 5 are slightly wavy. Nevertheless, the general trend of the simulated data is highly indicative. Based on the energy demands of the island, the microturbine, mechanical chiller and the auxiliary boiler are sized at 780 kW, 1000 kW and 230 kW, respectively.

4.2. Case 1: Peak shaving strategy

Due to the high costs of renewable energy technologies and hydrogen-related technologies, we propose peak shaving schemes. Peak shaving strategies have previously been investigated for the islands of Porto Santo and Sal [5] whereby excess renewable electricity is used by electrolyzer, stored as hydrogen, and during peak periods, hydrogen is used by a fuel cell system to produce electricity for the grid. Another work employs a solar load controller with a PV system to implement peak shaving [59]. According to this study, the use of the solar load controller enhances peak demand reduction by mitigating end-use load drivers in response to critical load situations. In both of these studies, the peak shaving strategy has improved system efficiencies and reduced extreme power loading during critical load periods.

The rationale for this part of the study is to investigate the scenario whereby renewable energy such as solar power supports the peak loads. In this strategy, the role of renewable energy technologies is to cover the hours of peak demands particularly when other prime movers are unable to support the full load. Another motivation of employing this scheme is attributed to the sizeable cooling demand throughout the year. Sizing the prime mover at a higher capacity would incur a higher output of cogenerated heat and increases the system's reliance on absorption chiller for cooling. In this scheme of operation, the microturbine is first sized at 520 kW. Due to the poor conversion efficiency of absorption chiller, the absorption chiller is sized at 512 kW so that there is minimal added heat required to drive the chiller. In order to handle the peak cooling load, mechanical chillers are set to operate when absorption chillers are unable to meet the cooling load demand.

4.3. Case 2: 20% Renewable energy penetration

The rationale of employing this scheme is to provide a certain degree of renewable energy penetration without discounting the merits of tri-generation systems in their simultaneous provision of cooling and power. In this strategy, the microturbine is designed for continuous operation throughout the year providing for 80% of the total electricity demand of the island, i.e. sizing the fossil fuel based microturbine at 430 kW. The absorption chiller is then appropriately sized at 418 kW to minimize the inefficient use of energy. The additional electrical power required by the mechanical chillers based on the total electricity load can be apparent from the load duration curve in Fig. 5. The remaining 20% of the power requirements are then provided by the integration of the various renewable energy technologies.

4.4. Case 3: 40% Renewable energy penetration

The environmental benefits of renewable energy technologies potentiate the implementation of a higher degree of renewable energy penetration. Hence, a 40% penetration level is also being investigated. This level of penetration presents a scenario of relatively high renewable energy technologies utilization, bolstering towards the realization of transforming the island into a 'green' one. In this strategy, the microturbine is sized at 365 kW to provide for 60% of the total electricity load. Consequently, the absorption chiller is sized appropriately at 330 kW to minimize additional heat required to drive the absorption chiller. Judging from the cooling load duration curves in Fig. 5, it is apparent that the absorption chiller is not able to sustain the cooling load at any point of time. In this regard, the support of the mechanical chillers is necessary to cater for periods of large cooling load. The remaining 40% of the power demand is contributed through the power generation from various renewable energy technologies.

5. Results and discussion

The proposed and designed tri-generation system will be evaluated based on its economic costs, energy efficiency and environmental benefits in order to evolve a cost-effective, energy efficient and "green" hybrid tri-generation system.

5.1. SSD and PV performance under DNI

The mean irradiation level in Singapore is comparatively higher during the first six summer months of the year. In order to demonstrate how the CCHP system performs with varying DNI (Direct Normal Irradiation), simulations of the energy outputs of the SSD and PV plants were performed using the TRNSYS software.

The varying monthly net field power production of both SSD and PV plants is computed and shown in Fig. 6. It is expected that the plausible amount of energy harvested by both plants varies accordingly to the DNI. Peak energy harvested for SSD and PV occurred in the month of February are 11.8 and 5.5 GWh, respectively. In addition, the energy collected for SSD is approximately two times that of PV. This is not surprising as SSD is known to sustain a daily conversion of solar beam to electricity of 24% with a peak efficiency of 29.4% [60] while latest numbers have shown that typical PV (monocrystalline silicon) efficiency spans 15–17% [61].

5.2. Primary energy savings

Fig. 7 presents the primary energy savings ratio of the individual cases. Generally, case 1 offers the best option in terms of achieving the primary energy savings ratio amongst the three

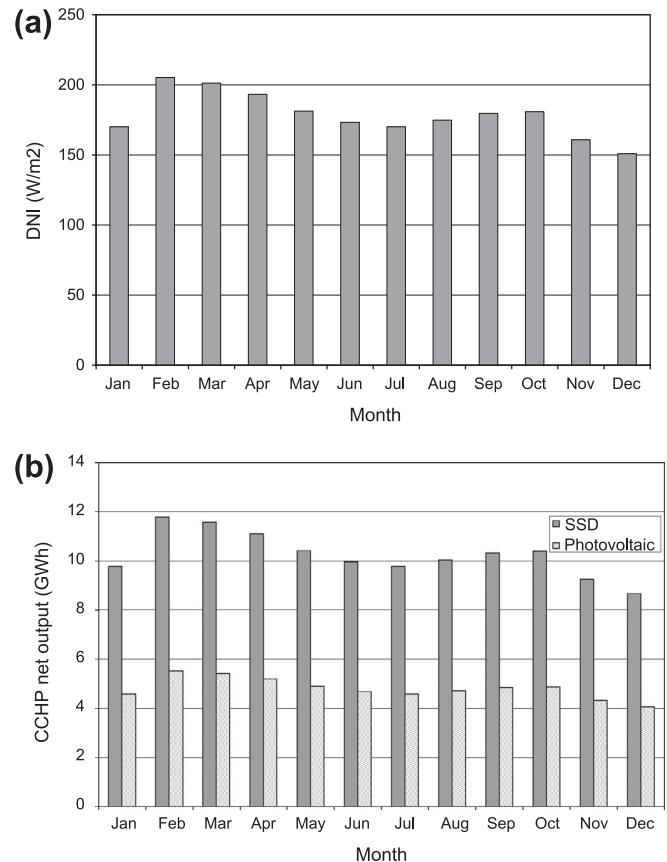


Fig. 6. (a) Average direct normal radiation per month; and (b) power outputs for SSD and photovoltaic versus months of a year.

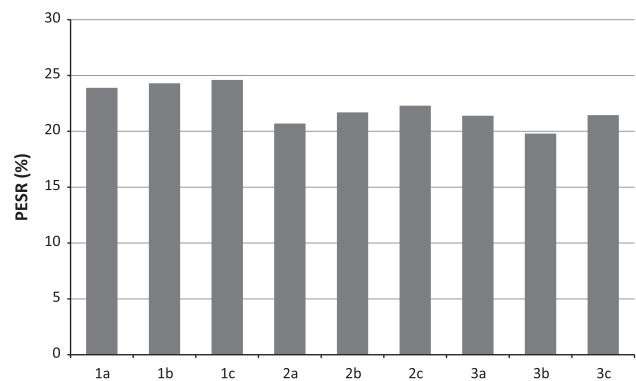


Fig. 7. Primary energy saving ratio (PESR) for individual cases (1a–c, 2a–c, 3a–c).

cases. Results also suggest that the use of a large capacity absorption chilling system would realize greater efficient use of primary energy fuel.

In general, there is a larger reliance on biomass plant for power generation in cases 2 and 3. It is generally observed that in cases 2 and 3, the primary energy savings ratios do not differ significantly. Due to the cogeneration capability of the biomass plant, the biomass plant supplements the heating needs of the island. A greater utilization of the biomass plant would lead to a reduced reliance on the auxiliary boiler to provide for the heating demand. This, in turn, would reduce the consumption of natural gas for auxiliary heating purposes.

It is also interesting to note that larger renewable energy penetration does not necessarily mean a greater savings in terms of fuel consumption. It may be attributed to the significant cooling de-

mand of the island. The use of the absorption chiller plays a vital role in lowering the cooling load on the mechanical chiller, thereby reducing the total electrical demand. For instance, by comparing case 2 and case 3, we are not able to reap much primary energy savings despite an increase of 20% in renewable energy penetration. In contrast, case 1 provides higher primary energy savings as compared to case 2 despite a similar increase in renewable energy penetration. The preceding discussion leads us to appreciate the importance absorption chiller cooling capacity and the selection of the prime movers in deriving the optimum primary energy savings.

5.3. Carbon emission savings

Fig. 8 illustrates the carbon dioxide emissions saving ratios (CESR) for different cases. It is observed that CESR increases with greater renewable energy penetration levels. In general, cases 2 and 3 showed an appreciable increase in carbon savings when compared to case 1. This is to be expected as the key factor in the reduction of carbon emission is the level of renewable energy penetration. Sharp increases in the reduction in carbon dioxide emission are observed with increasing employment of renewable energy. Within each case (e.g. 1a–c), the mix of renewable energy technologies does not markedly impact the reduction of carbon dioxide emissions. In cases 2 and 3, biomass power generation played a huge role in supplementing for the electrical demand (up to 30%) whereas in case 1, biomass power generation contributed to a mere approximately 5% of the total electricity demand. Apparently, the relatively insignificant indirect carbon emission from biomass (62.5 g-CO₂/kW h) as compared to the direct carbon emission from natural gas (370 g-CO₂/kW h) is the largest contributory factor in lowering the carbon dioxide emissions. Case 3b exhibits the highest carbon dioxide emission savings ratio of 47%. This is attributed to the higher renewable energy penetration as well as the higher installed capacity of SSD systems which offers the lowest in terms of carbon dioxide emission amongst the different renewable energy technologies.

Carbon trading mechanisms have been implemented in several industrialized countries to encourage the use of renewable energy technologies and reduction in carbon emission [42]. Under this scheme, emitters of carbon dioxide have to obtain certificates to legislate the certain amount of carbon dioxide imposed on them yearly. For those who cannot meet the cap must purchase credits, thus bringing their emissions into a compliance level with the cap. These certificates can be traded with others on a carbon exchange trading market mechanism. In this study, a value of US\$16/tonne-CO₂ is assumed to investigate the effect of carbon trading on the individual cases [43]. In subsequent sections, the carbon savings will be financially quantified.

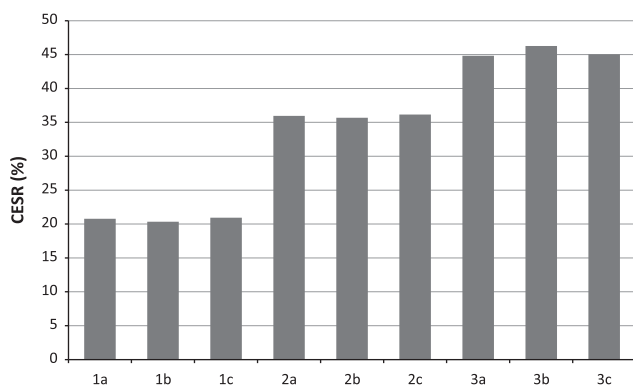


Fig. 8. Carbon dioxide saving ratios (CESR) for various cases comparing to the reference one.

5.4. Annualized life cycle cost savings

Annualized life cycle savings costs provides an assessment from the viewpoint of economic decision makers to make comparisons on the potential annual cost savings that can be derived from the implementation of the projects against a reference case. In this study, a discount rate, d , of 6% and a scenario of no fuel escalation are considered. Fig. 9 shows the annualized economic savings that are derived from the integrated energy systems taking into account the effect of carbon credits. The fuel escalation rate is assumed to be zero, i.e. $e = 0$. The effects of fuel escalation shall be discussed in the next subsection. Evidently, the savings that can be derived from carbon credit plays a modest role in the total savings one can derive from implementation of the project. The carbon credits savings that can be derived from the project constitutes to about 7% of the total annual cost savings as in case 1 and approximately 14% as in case 2.

It can be observed for cases 1 and 2 that annual savings can be derived from implementing the tri-generation system; making investments in the project worthwhile from the viewpoint of economic decision makers. On the contrary, case 3 presents a negative annualized life cycle savings which translates to negative economic benefits. Comparing case 3 to case 1 and case 2, the savings that can be derived from carbon credit as a result of the increased renewable energy technology penetration is significantly higher. Despite the larger savings, case 3 portrays an uneconomical scenario for investment despite its enhanced performance after incorporating environmental benefits. We attribute this observation to the higher utilization of both PV and SSD in contrast to cases 1 and 2. Albeit case 3 yielding favorable environmental outcome in terms of reducing carbon emission, the initial capital cost of PV and SSD to generate per kWh of energy to improve energy efficiency dilutes the positive benefits of good environmental performance.

The annual savings that can be derived from case 1 and case 2 spans US\$ 110,000 to USD \$150,000 per annum. These results suggest that there is no significant difference in terms of annualized life cycle savings between the two strategies. However, with the anticipated higher carbon emission credit that will be imposed in the next few years, the economic benefits of a case of higher renewable energy penetration may become appealing.

5.5. Effect of fuel escalation rate

Due to the soaring prices of fossil fuels, the effect of the escalating fossil fuel price on energy system is of particular real interest to system developers and end-users. We further analyze the impact of gradual increase of the fuel escalation rates on the different cases. Due to the similarity in the annual natural gas consumptions within each sub-cases (i.e. cases 1a–c, etc.), the average values of

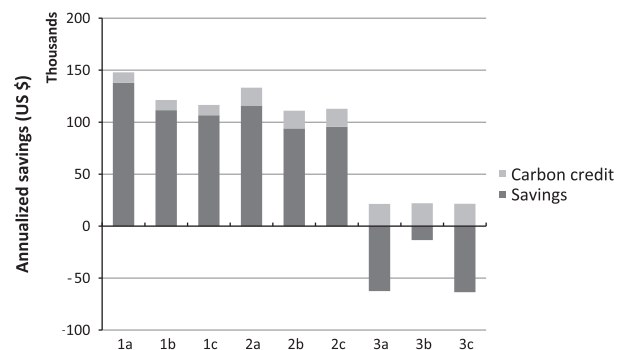


Fig. 9. Annualized life cycle cost savings for different cases.

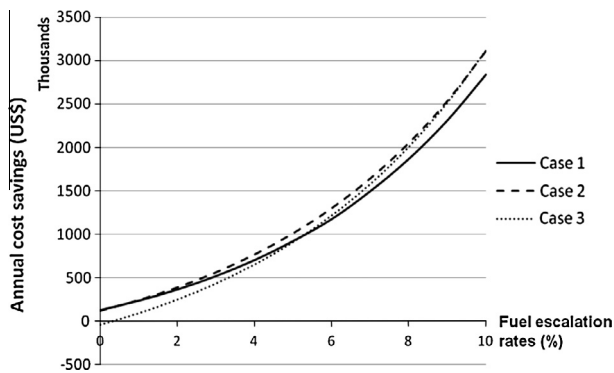


Fig. 10. Effect of fuel escalation rate on annual cost savings.

the annualized life cycle cost savings was taken into comparison to assess the effect of escalation of fuel prices instead. Fig. 10 presents the effect of fuel escalation rate on the potential annual savings. Comparing cases 1 and 2, the economic benefits of case 2 diverges at higher fuel escalation rates. This is attributed to the lower fuel consumption in case 2. In light of soaring fuel prices, case 2 generally offers a highly attractive economic solution in powering the island. Comparing case 3 to case 2, the curve for case 3 only intersects at high fuel escalation rates of about 7%. Comparing cases 2 and 3, the economic benefit derived from case 3 is apparently lower even at higher fuel escalation rates. Hence, it can be inferred that case 2 presents the most economically viable option among the 3 cases.

6. Conclusions

An integrated energy system model, comprising microturbines (capacity: 365–520 kW), photovoltaic (capacity: 200–750 kW), solar Stirling dish (capacity: 125–1000 kW), fuel cell system (capacity: 200–350 kW), biomass power plant (capacity: 150–300 kW), has been developed. Individual systems with different installed capacities were evaluated on a case by case basis in terms of their economic benefits, environmental impact and energetic efficiency. Key results that emerged from this study can be summarized as follows:

- (1) An integrated renewable energy system has been designed in order to evolve a tri-generation system that is able to sustain the energy benefits;
- (2) a renewable energy penetration level of 20% offers comparable economic savings of up to USD\$130,000 per annum and enables a reasonable carbon dioxide reduction of approximately 1000 tonnes of CO₂ equivalent per year. In terms of primary energy savings, this scenario offers a reduction of approximately 21% in primary energy consumed; and
- (3) a renewable energy penetration level of 40% resulted in the highest reduction in carbon dioxide emission and an acceptable primary energy savings ratio of up to 23%. However, results have indicated that annual economic losses would be incurred if the project is to be implemented at 40% penetration. This is largely due to the higher utilization of both PV and SSD which incur much higher capital costs. At higher fuel prices, 40% of renewable penetration potentially becomes economically viable.

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